

Gamma-ray sources like V407 Cygni in Symbiotic Stars

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ABSTRACT

Using a simple accelerating model and an assumption that γ -rays originate from $p-p$ collisions for a π^0 model, we investigate γ -ray sources like V407 Cygni in symbiotic stars. The upper limit of their occurrence rate in the Galaxy is between 0.5 and 5 yr^{-1} , indicating that they may be an important source of the high-energy γ -rays. The maximum energies of the accelerated protons mainly distribute around 10^{11} eV, and barely reach 10^{15} eV. The novae occurring in D-type SSs with ONe WDs and long orbital periods are good candidates for γ -ray sources. Due to a short orbital period which results in a short acceleration duration, the nova occurring in symbiotic star RS Oph can not produce the γ -ray emission like that in V407 Cygni.

Key words: binaries: symbiotic—stars: individual (V407 Cygni)—acceleration of particles—cosmic rays

1 INTRODUCTION

Symbiotic stars (SSs) are usually interacting binaries, composed of a cool star, a hot component and a nebula. The hot component is usually a white dwarf (WD). The cool component is either a normal red giant (RG) in S-type or a Mira variable surrounded by an optically thick dust shell in D-type. Symbiotic novae are a small subclass of thermonuclear novae which occur on a WD surface fueled by mass accreted from an RG. They can produce super-soft or soft X-ray emission in SSs (Mürset et al. 1997; Zhu et al. 2010).

V407 Cygni is a D-type SS consisting of a Mira-type pulsating RG. Recently, Abdo et al. (2010) reported the *Fermi* Large Area Telescope detection of variable γ -ray emission (0.1–10 GeV) from the nova of SS V407 Cygni. They explained that the γ -ray spectrum originate from proton-proton ($p-p$) interaction by π^0 model¹, but inverse Compton scattering (See Blumenthal & Gould (1970) for an exclusive review) of infrared photons from the RG by electrons cannot be ruled out. The above two mechanisms producing γ -rays need the high-energy protons or electrons. Cosmic rays with high energies are thought to originate from supernovae remnants (SNRs). In order to having an effi-

cient acceleration mechanism the theory of diffusive shock acceleration has been developed (see a recent review from Malkov & Drury (2001)). Diffusive shock acceleration applies only for particles with a Larmor radius larger than the typical shock thickness. If electrons and protons are equilibrium in the shock, the Larmor radius of electron is a factor $(m_e/m_p)^{1/2}$ smaller than that of proton, where m_e and m_p are masses of an electron and a proton, respectively. Only electrons which are already relativistic can cross the shock and start acceleration. Therefore, protons are accelerated more easily than electrons under the mechanism diffusive shock acceleration.

In this Letter, we investigate the likely possibility of the symbiotic novae producing γ -rays, then assume that γ -rays originate from $p-p$ collisions for a π^0 model, and investigate the γ -ray sources in SSs.

2 ACCELERATION MODEL

In general, the theory of diffusive shock acceleration is used for SNRs to explain the emission of cosmic rays with high energy. In this work the acceleration model used for the symbiotic novae like V407 Cygni is similar with that used for SNRs. There is usually a low particle-density circumstellar medium (CSM) around SNRs. However, a symbiotic nova like V407 Cygni is usually embedded in a dense CSM which is mainly formed from stellar winds lost by the red giant. This difference makes it possible to efficiently accelerate protons in the symbiotic novae.

According to the theory of diffusive shock acceleration

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¹ π^0 model is that secondary neutral pion decays γ -rays from proton-proton ($p-p$) collisions, i.e., the reaction considered is $p + p \rightarrow \pi^0 + X$ and the decay is $\pi^0 \rightarrow 2\gamma$, where p represents a proton, π^0 represents a neutral pion, and X represents any combination of particles (see the references of Kamae et al. (2006))

for SNRs, the maximum attainable energy for cosmic rays is determined by the size of accelerator, the magnetic field of the CSM and the energy losses resulting from adiabatic processes and synchrotron processes. The size depends on the explosion evolution of SNR. According to Kirk (1994), the explosion includes three phases: free-expansion phase, Sedov-Taylor phase and snow-plough phase. During the free-expansion phase, the kinetic energy of ejecta remains untapped, and the particle acceleration is not significant. Once the mass swept-up by the shock becomes comparable to the mass of the ejecta M_{ejc} , the explosion enters the Sedov-Taylor phase. The acceleration efficiency is the highest in this phase. The maximum energy for protons is approximately given by (Schure et al. 2010)

$$E_{\text{max}}^{\text{p}} = \frac{3ZeBV_{\text{sh}}^2 t_{\text{ST}}}{\xi_{\sigma} c} = \frac{3ZeBV_{\text{sh}} R_{\text{ST}}}{\xi_{\sigma} c} \quad (1)$$

where Z is the charge number, e is the elementary electric charge, c is the speed of light and ξ_{σ} is a relation between the compression ratio of the density and magnetic field. Here, we assume that the magnetic field is parallel to the shock normal, which means $\xi_{\sigma} = 20$. B is the magnetic field strength, and $t_{\text{ST}} \sim R_{\text{ST}}/V_{\text{sh}}$ is the duration for which the particles stay in the Sedov-Taylor phase, where V_{sh} is the shock speed and R_{ST} is the radius where the shock sweeps up the matter whose mass is equal to that of the ejecta.

In general, for SNRs, the magnetic field B of the CSM is $\sim \mu\text{Gauss}$, and R_{ST} is $\sim \text{pc}$ due to the high mass of the ejecta ($\sim M_{\odot}$) and the low particle density of CSM (McKee & Truelove 1995). Typical t_{ST} is several hundred years. However, in symbiotic novae like V407 Cygni, there are some physical conditions which are greatly different from those in SNRs:

(i) The magnetic field of the CSM is the magnetic field of the stellar wind from the RG, and it is given by Bode et al. (1985)

$$B = \sqrt{8\pi\rho kT_{\text{g}}/\bar{m}} \quad (2)$$

where k is Boltzmann's constant, $\bar{m} = 10^{-24} \text{ g}$ is the mean particle mass, and T_{g} is the temperature of the stellar wind. V407 Cygni is a D-type SS in which the RG has dust shells. The temperature for the dust condensation zone is $\sim 1000 \text{ K}$ Gail & Sedlmayr (1999). Here, we take $T_{\text{g}} = 1000\text{K}$. The density ρ is given by

$$\rho = \frac{\dot{M}_{\text{L}}}{4\pi V_{\text{w}}(R^2 + a^2 - 2Ra \cos \theta)} \quad (3)$$

where \dot{M}_{L} is the mass-loss rate of the RG, V_{w} is the stellar wind velocity, a is the binary separation, a distance R and polar angle θ is from the WD center towards the RG. For simplicity, we only consider $\theta = 0^\circ$. As shown by Bode et al. (1985), B is $\sim 10^{-2} \text{ Gauss}$, which is 10^3 times higher than that in the CSM of SNR.

(ii) For a typical nova, the mass of ejecta is $\sim 10^{-6} M_{\odot}$ (Yaron et al. 2005), which is much less than that of the ejecta in a typical supernova. Furthermore, we note that the duration of matter ejecting in a typical nova is \sim several days or tens of days, and the matter ejected has an average expansion velocity V_{av} over the whole ejecting matter phase and a maximal expansion velocity V_{max} . This means that a part of the matter ejected has the high expansion velocity V_{max} . The shock in a nova is mainly produced by the matter

ejected with high velocity. We assume that $V_{\text{sh}} = V_{\text{max}}$, and use a parameter η to define a ratio of the mass ejected with a velocity of V_{max} to the whole ejecta. R_{ST} can be given by the following equation:

$$\eta M_{\text{ejc}} = \int_{R_{\text{WD}}}^{R_{\text{ST}}} 4\pi R^2 \rho dR \quad (4)$$

where R_{WD} is the radius of WD. Abdo et al. (2010) found that the peak flux in γ -rays was observed after 3-4 days of a nova outburst from V407 Cygni on 10 March 2010. This implies that t_{ST} in V407 Cygni should shorter than 3 days. In our model t_{ST} depends on the parameter η . We find that $t_{\text{ST}} \sim$ days when $\eta \sim 0.01$.

The novae occurring in SSs are surrounded by the dense stellar winds from the RGs. They offers an environment for high efficient particle acceleration. Therefore, they may be an important source of the high-energy γ -rays in the Galaxy.

3 SYMBIOTIC STARS

In general, SSs are the detached interacting binaries in which the WDs accrete the matter of the RGs via stellar winds. By a population synthesis method, Lü et al. (2006) carried out a detailed investigation of SSs. They found that the occurrence rate of the novae in SSs is greatly affected by common-envelope evolution and the stellar wind velocity V_{w} of the RG. Following Lü et al. (2006) and Zhu et al. (2010), for common-envelope evolution in different simulations we use an $\alpha_{\text{ce}}\lambda_{\text{ce}} = 0.5$ in α -algorithm and $\gamma = 1.75$ in a γ -algorithm, respectively; for the stellar wind, $V_{\text{w}} = \frac{1}{2}v_{\text{esc}}$ where v_{esc} is the escape velocity and V_{w} is determined by the relation between the mass-loss rates and the terminal wind velocities fitted by Winters et al. (2003) as:

$$\log_{10}(\dot{M}/M_{\odot}\text{yr}^{-1}) = -7.40 + \frac{4}{3}\log_{10}(V_{\text{w}}/\text{km s}^{-1}). \quad (5)$$

In this work we consider three cases with different input parameters:

- (i) in case 1, $\alpha_{\text{ce}}\lambda_{\text{ce}} = 0.5$ and $V_{\text{w}} = \frac{1}{2}v_{\text{esc}}$;
- (ii) in case 2, $\gamma = 1.75$ and $V_{\text{w}} = \frac{1}{2}v_{\text{esc}}$;
- (iii) in case 3, $\alpha_{\text{ce}}\lambda_{\text{ce}} = 0.5$ and V_{w} taken as Eq. (5).

Using the model of SSs and grid for novae in Yaron et al. (2005), we can estimate $E_{\text{max}}^{\text{p}}$ in which $\theta = 0^\circ$ and $\eta = 0.01$ for every nova. According to Kamae et al. (2006), $p-p$ interaction can occur when the energy of proton is higher than 10^9 eV , which results in γ -ray emission. Therefore, we assume that the novae in SSs are γ -ray sources if the $E_{\text{max}}^{\text{p}}$ in Eq. (1) is higher than 10^9 eV .

4 RESULTS

Using a population synthesis method described in Lü et al. (2006, 2008), we model 10^6 binary systems which gives a statistical error for our Monte Carlo simulation lower than 5 percent for the symbiotic novae. In order to estimate the occurrence rate of the γ -ray sources like V407 Cygni, we assume one binary with primary mass more massive than $0.8 M_{\odot}$ is formed annually in the Galaxy. We do not consider the energy losses of the accelerated protons via adiabatic process and synchrotron process. Therefore, we overestimate

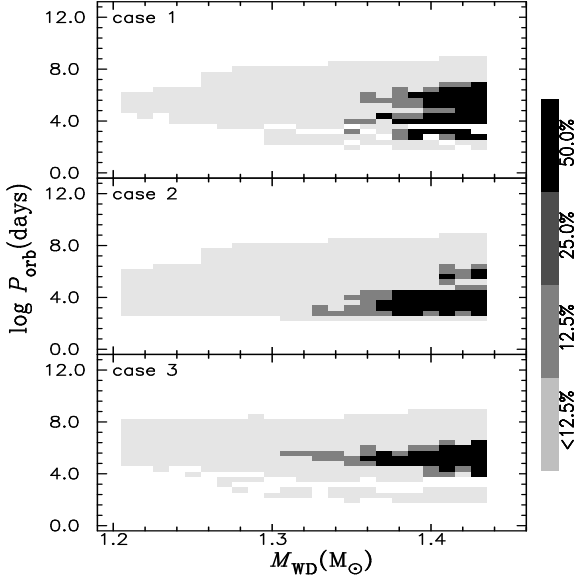


Figure 1. Gray-scale maps of WD’s masses vs. orbital periods for SSs as γ -ray sources in cases 1, 2 and 3. The gradations of gray-scale correspond to the regions where the number density of systems is, respectively, within $1 - 1/2$, $1/2 - 1/4$, $1/4 - 1/8$, $1/8 - 0$ of the maximum of $\frac{\partial^2 N}{\partial \log P_{\text{orb}} \partial M_{\text{WD}}}$, and blank regions do not contain any stars.

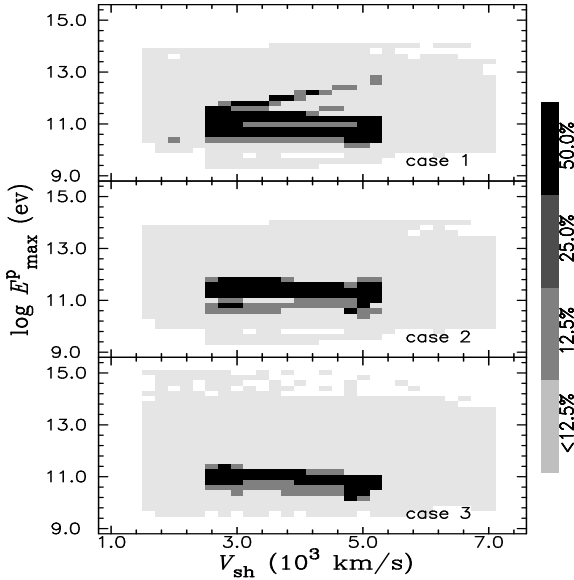


Figure 2. Similar to Figure 1, but for the maximum energy E_{max}^p of the protons accelerated vs. the shock velocity V_{sh} .

the maximum energy of the proton and the occurrence rate of the γ -ray sources in this work.

We select symbiotic novae as γ -ray sources if E_{max}^p of the accelerated protons is larger than 10^9 eV. Our model shows that the upper limits of the occurrence rates of γ -ray sources like V407 Cygni in SSs are 0.5 yr^{-1} in case 1, 2.0 yr^{-1} in case 2 and 5.0 yr^{-1} in case 3, respectively. Compared with the results in Lü et al. (2006), about 15% of the novae in SSs for cases 1 and 2 can produce γ -ray emission, and it is 40% in case 3 because the wind velocity in Eq.(5) is favorable for a strong nuclear outburst. If the Galactic cos-

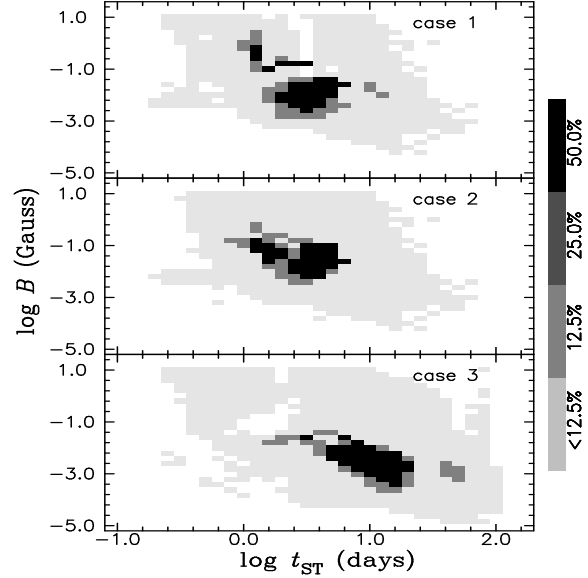


Figure 3. Similar to Figure 1, but for the duration of Sedov-Taylor phase t_{ST} vs. the magnetic field of the stellar wind from RGs.

mic rays originate from the supernova whose occurrence in the Galaxy is $\sim 0.01 \text{ yr}^{-1}$, we suggest that symbiotic novae like V407 Cygni may be another important source of the high-energy γ -rays. However, the contribution of the symbiotic novae to total cosmic rays cannot be known until the spectra-energy distribution of the γ -rays from the novae is calculated, which will be carried out in further work.

Figure 1 shows the distribution of the WD’s masses vs. orbital periods for SSs as γ -ray sources. Majority of WDs in these SSs are ONe WDs and they have masses larger than $1.3 M_{\odot}$. As Lü et al. (2008) mentioned, the most significant property of novae occurring on the surface of ONe WDs is high neon abundance in the ejected materials. V407 Cygni may offer a chance to investigate the thermonuclear outbursts on the surface of ONe WDs. However, to our knowledge, there is no observational data on the neon abundance of the ejecta in this nova from V407 Cygni. The peak of orbital-period distribution is around $\sim 10^5$ days in cases 1 and 3, and it is around $\sim 10^3$ days in case 2. Munari et al. (1990) suggested that the V407 Cygni has an orbital period of 43 years, which is consistent with our results. Novae in SSs with long orbital periods mean that RGs have high mass-loss rates. In our work, the majority of the RGs have mass-loss rates higher than $5 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. Ferrarotti & Gail (2006) suggested that RGs produce significant dust when their mass-loss rates are higher than $3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. Therefore, we consider that most of SSs as γ -ray sources have massive WDs, long orbital periods and RGs with dust shells. This means that the novae occurring in D-type SSs with ONe WDs are good candidates for γ -ray sources.

RS Oph is a symbiotic recurrent nova which had previously undergone recorded outbursts in 1898, 1933, 1958, 1967 and 1985. It comprises a red giant star in a 455.72 ± 0.83 day orbital period with a white dwarf (WD) of mass near the Chandrasekhar limit. Recently, RS Oph was observed to be undergoing an outburst On 2006 February 12.83 UT (Hirosova 2006). During the first 3 days a hard X-ray emis-

sion (14-25 keV) was clearly detected, and there was a weak detection in the 25-50 keV band immediately following the outburst (Bode et al. 2006). After that, the X-ray spectrum in RS Oph was seen to evolve from the relatively hard to a super-soft source state (Evolutionary details are in Nelson et al. (2008)). However, there is no conclusive evidence for gamma-ray emission like V407 Cygni in the 2006 outburst. The orbital period of V407 Cygni is ~ 40 times that of RS Oph, which means that the density of CSM around the WD in the later is higher than 100 times of that in the former if $\frac{\dot{M}_L}{V_w}$ is comparable in the two binaries². Therefore, the duration of the diffusive shock acceleration in 2006 outburst of RS Oph, t_{ST} , is too short so that protons and electrons can not be accelerated enough energy to produce γ -ray emission.

Figure 2 gives the distribution of E_{\max}^p vs. V_{sh} . The peak of E_{\max}^p is at $\sim 10^{11}$ eV, and E_{\max}^p hardly reaches 3×10^{15} eV which is the knee of the cosmic ray spectra. If the γ -ray energy originating from $p-p$ interaction is comparable to E_{\max}^p , they should be in the low-frequency part of high-energy cosmic rays. These nuclear outbursts are very strong so that the ejecta have high velocity. As Figure 2 shows, V_{sh} in the symbiotic novae is \sim several 10^3 km/s. According to the calculations of Yaron et al. (2005), in these strong nuclear outbursts most of the accreted mater is expelled and in some cases even an erosion of the WD occurs. Therefore, the massive WDs in γ -ray sources do not explode as supernovae.

Figure 3 shows the distribution of the duration of Sedov-Taylor phase t_{ST} vs. the magnetic field of the stellar wind from RGs. The peaks of the magnetic field distribution are around $\sim 10^{-2}$ Gauss in cases 1 and 2, and it is around $\sim 10^{-3}$ Gauss in case 3 because a high mass-loss rate results in high V_w (See Eq. (5)). The magnetic fields of the stellar winds around the novae in SSs are 10^3 times higher than those of CSM around SNRs. The peak of t_{ST} is at ~ 3 days in cases 1 and 2, while it is around ~ 10 days in case 3 due to a high V_w which results in the low density of stellar wind. However, as mentioned in the §2, t_{ST} are greatly affected by an uncertain parameter η .

5 CONCLUSIONS

In this Letter, we use a toy model to investigate the γ -ray sources which originate from $p-p$ collisions in the novae of SSs. The symbiotic novae occurring on the surface of accreting WDs are surrounded by the dense stellar winds from the RGs. They offers an environment for highly efficient particle acceleration. We estimate that the upper limit of the occurrence rate of γ -ray sources in SSs in the Galaxy is between 0.5 and 5 yr^{-1} . Therefore, they may be an important source of the high-energy γ -rays. The maximum energies of the accelerated protons mainly distribute around 10^{11} eV, and barely reaches 10^{15} eV. If the γ -ray energy originating from $p-p$ interaction is comparable to E_{\max}^p , they should

be in the low-frequency part of high-energy cosmic rays. In SSs as γ -ray sources, majority of WDs are ONe WDs and have masses larger than $1.3M_{\odot}$, and most of RGs have dust shells. The novae occurring in D-type SSs with ONe WDs are good candidates as γ -ray sources. Due to the short orbital period, the nova occurring in RS Oph hardly produces γ -ray emission like that in V407 Cygni.

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² Munari et al. (1990) estimated that the mass-loss rate of the RG in V407 Cygni is $\sim 6 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. Considering no thick dust shells around RS Oph, we assume that the mass-loss rate of the RG in RS Oph is $\sim 10^{-7} M_{\odot} \text{ yr}^{-1}$. However, due to the dust-driven wind (Gail & Sedlmayr 1986), the stellar wind velocity V_w in V407 Cygni is higher than that in RS Oph